Original Article

Institution of MECHANICAL ENGINEERS

Journal of RAIL AND RAPID TRANSIT

Proc IMechE Part F:
J Rail and Rapid Transit
2017, Vol. 231(8) 835–849

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DOI: 10.1177/0954409716647094
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Evaluation of the longitudinal restraint, uplift resistance, and long-term performance of high-density polyethylene crosstie rail support system using static and cyclic loading

Ibrahim Lotfy and Mohsen A Issa

Abstract

Rail track longevity is a primary concern for the railroad industry in the US. Therefore, it is important to study the rail support system in detail. This includes understanding the interactions between the rail, the different fastening components, and the crosstie. Then evaluate the support system's long-term performance. Over the past several years, the railroad industry in the US has been leaning toward implementing alternative solutions to the traditional hardwood timber crossties. Recycled plastic composite crossties present an appealing and effective solution due to their sustainably, environmental benefits, durability, and ease of installation. Several US manufacturers are currently offering commercial crosstie solutions using different recycled plastic composite materials. Thousands of composite plastic crossties are currently in service in a wide variety of railroad tracks. Researchers have investigated this material in the past; however, additional research is still needed to fully understand the rail support system and its long-term behavior. This paper presents an experimental investigation aiming to understand and assess the performance of the full rail support system: the rail section, fastening assembly, and recycled high-density polyethylene crossties. The study encompassed a comprehensive experimental investigation using static and cyclic test methods recommended by the American Railway Engineering and Maintenance-of-Way Association manual. The static tests addressed the performance of the rail support system when subjected to uplift forces and longitudinal loading in the direction of the rail track, e.g. breaking and traction forces. The dynamic test evaluated the long-term behavior of the rail support system while being subjected to repeated loading for three million fatigue cycles. The outcomes of this study showed great results; the crossties survived the fatigue loading with normal wear and minimal degradation, which highlights the potential of these materials if properly optimized and engineered.

Keywords

Railroad crossties, high-density polyethylene, fatigue testing, experimental testing, finite element modeling

Date received: 18 March 2015; accepted: 4 January 2016

Introduction

Rail track longevity is a primary concern for the railroad industry in the US. Thus, in an effort to enhance the durability and life cycle cost efficiency of crossties, the railroad industry is increasingly leaning toward implementing alternative solutions to the traditional hardwood timber. Aside from deforestation concerns, hardwood timber crossties are vulnerable to rot and organic decay, drastically limiting their service life, which forces the manufacturers to use wood preservatives, e.g. creosote, which are subject to much debate due to health concerns.[1–5]

One of the available alternative materials for railroad crossties is recycled engineered composite plastic. Recycled composite plastic crossties can be engineered to meet the required performance criteria while maintaining the same geometry and weight as its timber counterparts, thus enabling one-to-one replacement strategies.[6] Moreover, its inherent damping and durability can result in a prolonged service life with enhanced rideability and passenger comfort. These benefits render recycled plastic crossties a

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competitive solution fitting for both new and replacement operations of railroad crossties. Moreover, recycling plastic waste is a green process, which is very appealing in today's modern society that has a greater awareness of environmental issues.

Recycled plastic composite crossties have numerous and apparent environmental and structural advantages ranging from pollution and waste reduction to life cycle cost efficiency.[6–9] Subsequently, several US manufacturers are currently offering commercial crosstie solutions using different recycled plastic composite materials and thousands of plastic crossties are currently in service in a wide variety of railroad tracks.[10]

Past research

Recycled composite plastic crossties have been studied by researchers in the past using experimental laboratory and field testing. Jimenez[11] conducted an experimental investigation to evaluate the vertical track modulus of curved tracks using plastic and wooden crossties. Lampo et al.[12] investigated the performance of the composite crossties through several laboratory and field tests. The fatigue performance of composite crossties was investigated in a study conducted by Roybal.[13] He performed a cyclic test on a half section of crosstie using cut spikes to fasten the rail and the steel bearing plate to the crosstie. The composite plastic crossties demonstrated adequate performance with normal wear and abrasion in the tie plate area and did not have any cracks or anomalies. Reiff and Trevizo[14] performed a series of experimental tests on three types of plastic composite crossties to investigate the effect of several factors on the performance of the crossties such as temperature variation, type of spikes used, and effect of impact forces. They concluded that the plastic composite crossties showed adequate performance, with high-density polyethylene (HDPE) reinforced with glass fiber showing the best performance out of the three types tested in terms of flexural stiffness and impact resistance.

As evident from the past studies, limited research data are available on composite plastic crossties and more specifically its long-term performance. Moreover, the prevalent US rail manual, the American Railway Engineering and Maintenance-of-Way Association (AREMA) manual, does not yet have fully developed criteria for composite crossties testing.[15] Therefore, additional research is necessary to properly characterize and describe the behavior of the rail support system and understand the interactions between the rail, the different fastening components, and the crosstie as well as assess its long-term performance.

Research objective

Sponsored by the New University Rail Center research program "U.S. DOT-RITA," the University of Illinois at Chicago conducted a series of studies to assess the feasibility of implementing HDPE crossties in both conventional and high-speed rail applications. The previous studies conducted by the authors explored the flexural performance of HDPE composite railroad crossties reinforced with discontinuous randomly distributed glass fibers and its sensitivity to temperature variations.[16,17] Additionally, a parametric experimental investigation was also conducted to assess the effect of predrilling, loading rate, temperature, and type of spike on the behavior of rail fastening spikes.[18] In this paper, the behavior of the entire system is being investigated using recommendations from the previous work. This paper presents an experimental investigation aiming to understand and assess the performance of the full rail support system, i.e. HDPE crosstie with the rail section and the fastening system installed. This includes understanding the interactions between the rail, the different fastening components, and the crosstie. Then the system's long-term performance was evaluated. The study encompassed a comprehensive experimental investigation using static and cyclic test methods recommended by the AREMA manual. The static test addressed the performance of the rail support system when subjected to vertical uplift forces as well as longitudinal loading in the direction parallel to the rail track, e.g. breaking and traction forces. The dynamic test evaluated the long-term performance of the rail support system while being subjected to repeated loading for three million fatigue cycles. This performance provides an indication of the expected service life of the crossties. The objective of this paper is as follows:

- Understand the behavior of the full system and the interactions between the rail, the different fastening components, and the HDPE crosstie;
- Evaluate the performance of the rail support system when subjected to longitudinal loading;
- Investigate the uplift behavior of the system and the contributions of each component of the fastening assembly to the uplift resistance;
- Assess the long-term performance of the rail support system;
- Identify any weak points in the system and recommend possible improvements/modifications.

Experimental program

Description of the crosstie and fastening assembly

The composite plastic crossties investigated in this study were made from HDPE and were reinforced with randomly distributed discontinuous glass fibers. They were manufactured through an extrusion process from recycled plastic milk and detergent bottles, of which 7.2 billion pounds (3.27 billion kilograms) are land filled each year in the US.[7] Foam inducing agents were used to control the density and cost of the final product. UV inhibitors and antioxidants were added to a thin skin surface layer to protect the surface of the crossties. These manufacturing procedures produced an efficient cross section with optimum distribution of the reinforcing fibers and minimal weight; however, it also creates a difference in the properties between the core and exterior regions of the cross section.[16] The final HDPE crosstie has sectional dimensions of 9×7 in. (22.86×17.78 cm), length of 8–9 ft (2.44–2.74 m), and an average density of 56.8 pcf (910 kg/m^3).

The fastening system components used in this study were provided by the Chicago Transit Authority (CTA). They corresponded to the same fastening components used for actual plastic composite crossties applications within the city of Chicago. Figure 1 shows the HDPE composite crosstie and the fastening system components used in this study. For each tested specimen, four rail screw spikes were used to fasten the steel bearing plate to the crosstie. The rail bearing pad was placed in between the rail section and the steel bearing plate to provide friction and elasticity while insulating electricity. Two fastening e-clips were used to clamp the rail to the steel bearing plate from each side while two plastic insulators were placed in between the clip toes and the rail to provide electric insulation. This configuration represents the typical fastening system used with engineered plastic composite crossties in the city of Chicago.

Testing equipment

A sophisticated universal testing machine, "Instron 8500 Series Servo-hydraulic Testing System," was used in this study for all the experimental evaluations. This system has an actuator with a capacity of $\pm$50,000 lb ($\pm$222.4 kN) and the capability of applying both static and dynamic loading. The system has a 26 in. (66 cm) wide rigid steel testing bed with a total length of 144 in. (365.7 cm). The system is highly controlled using four distinct controlling schemes: load, deflection, strain, and crack opening allowing for open and closed loop testing configurations.

Longitudinal restraint of rail support system

The longitudinal restraint experimental test was performed as per the AREMA manual recommendations: AREMA Part 2—Section 2.6.2—Test 5B.[15] It was conducted to measure the ability of the rail support system to resist longitudinal rail movement. This movement can occur as a result of longitudinal forces in the direction of the rail track, e.g. breaking and traction forces. The support system rigidity is very important to retain the track geometry and ensure constant gauge length to avoid derailment. Moreover, train acceleration, deceleration, and breaking require a rigid support to ensure proper traction with the wheels. The longitudinal track rigidity is provided by contributions from consecutive crossties and fastening systems. This test assesses only one of the rail supports in details, i.e. the interactions between the rail, fastening assembly, and HDPE crosstie. The support system resistance to longitudinal forces is expected to be a combination of the frictions between the rail and the underlying rail pad and steel bearing plate as well as the two insulator pads which are clamped to the rail by the prestrained, fastening e-clips. For this test, the crosstie specimens were cut into 24 in. (60.9 cm) long segments and the rail was cut into a 14 in. (35.56 cm) long segment. The full rail and fastening system assembly were installed to the crosstie specimen. The screw spikes were installed manually using an adjustable wrench with the predrilling configuration proposed by the authors in the previous study: "setup D" profile.[18] Seeing as the testing machine can only apply vertical loading, the specimens were rotated 90° and were fixed on their side in order to achieve the desired testing configuration. A wide flange steel I-beam was cut into a 24 in. (60.9 cm) long segment and was modified and stiffened

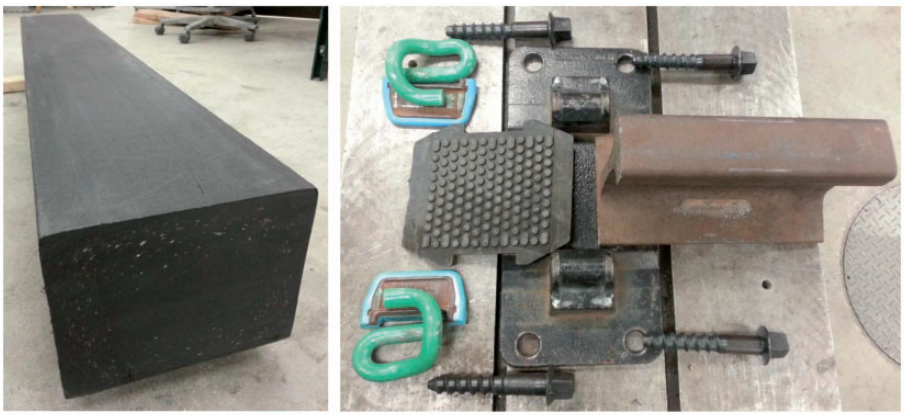

Figure 1. Rail, HDPE composite crosstie, rail section, and fasting system assembly. HDPE: high-density polyethylene.

with two steel pipe sections. This specially made I-beam was used to properly support the specimen while elevating it from the testing machine bed, which enabled free movement of the rail. Then six holes were drilled through the side of the specimens to properly fix them to the steel I-beam. The specimens were then fixed to the I-beam using six, 0.5 in. (1.27 cm), threaded rods and three, 1 in. (2.54 cm) thick, aluminum plates on the top. The loading was applied at the bottom edge of the rail cross section as per AREMA recommendations and five specimens were tested to increase the reliability of the results.

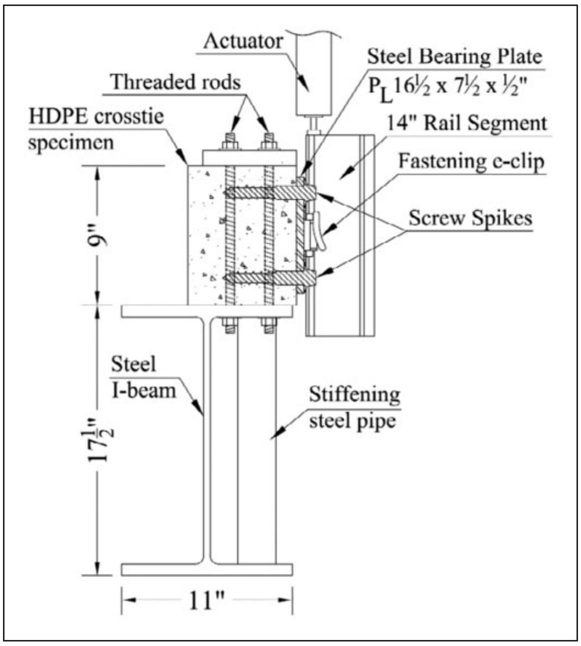

Figure 2. Longitudinal restraint test schematics (all units are in inches, 1″= 2.54 cm).

Figures 2 and 3 illustrate the longitudinal restraint test schematics and configuration.

The loading was applied as a downward displacement, perpendicular to the specimen, with a stroke-controlled loading rate of 0.05 in./min (0.13 cm/min) and the rail displacement was recorded with an accuracy of 1×10^{-5} in. (2.54×10^{-5} cm). The loading was applied until the rail section slipped by at least 0.2 in. (0.51 cm) from the fastening system. Figures 4 and 5 present the test results for the five tested specimens.

The tested specimens showed a behavior similar to friction behavior with two distinct phases. The first phase is the static friction phase where the specimens experienced no motion. After the maximum static friction (i.e. impeding motion friction) was reached, the second phase starts, which corresponds to kinetic friction where the specimens experience friction with motion. As mentioned earlier, this behavior is reasonable as the resistance to longitudinal straining actions is provided by friction between the rail, the underlying rail pad, the steel bearing plate, and the two insulator pads. Inspection of Figures 4 and 5 reveals that the maximum static friction was relatively inconsistent and varied slightly between the different tested specimens, which could be attributed to the different rail pads, the insulators used for each specimen, and the installation procedures. It is also noticed that, regardless of the maximum static friction, all the specimens were converging on a constant friction value as afterward, i.e. the kinetic friction. In addition, it is expected that the specimens' resistance will continue to level until they reach a constant friction force of about 3300 lb (14.68 kN). The AREMA manual recommends that the maximum longitudinal displacement at 2400 lb (10.67 kN) applied load is 0.2 in. (0.51 cm).[15] This threshold was established to limit

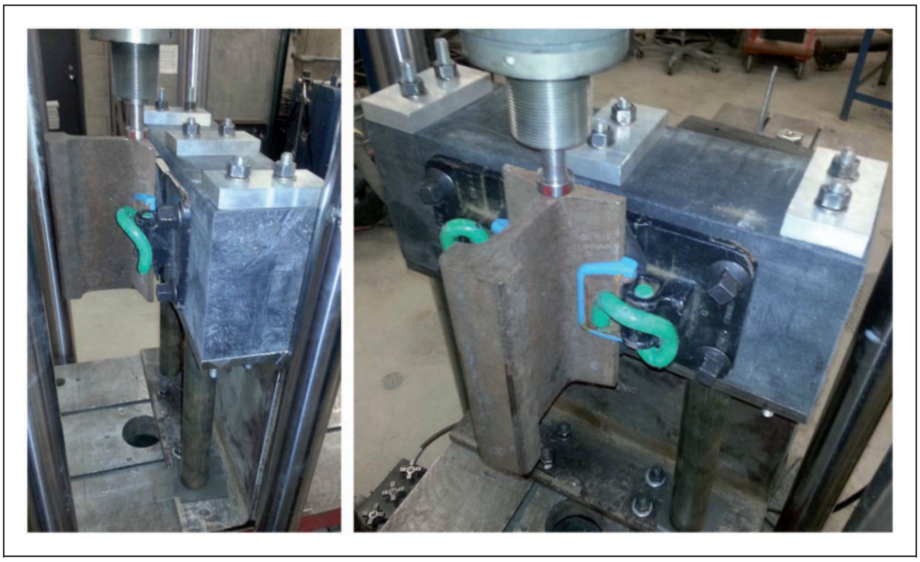

Figure 3. Longitudinal restraint test setup.

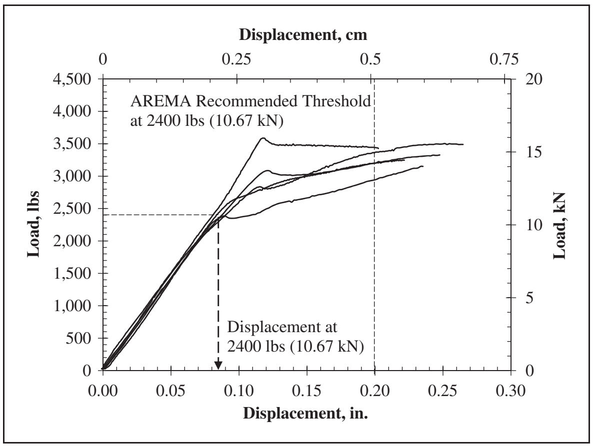

Figure 4. Longitudinal restraint test sample result.

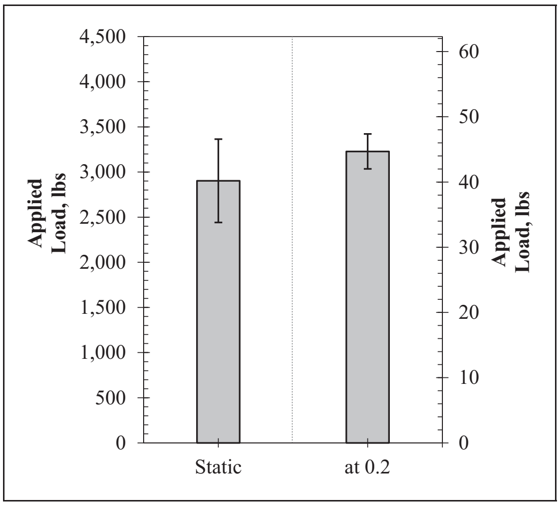

Figure 5. Longitudinal restraint test result summary for all the tested specimens.

alteration in the track geometry and ensure constant gauge length. As noticed from Figure 4, all the specimens experienced longitudinal displacements of about 0.09 in. (0.23 cm) at 2400 lb (10.67 kN) applied load, which surpassed the recommendations by a significant margin. It is also important to note that the maximum static friction for all the tested specimens was reached before 0.2 in. (0.51 cm) displacement, which is significant as the maximum static friction should not be reached under normal operating conditions in a properly designed system.

Fastener uplift

The fastener uplift test was performed following the AREMA recommendations: AREMA Part 2—Section 2.6.1—Test 5A.[15] It is used to measure the ability of the rail and fastener system to resist vertical uplift forces. The systems uplift resistance is provided by both the fastening clips and the screw spikes pullout resistances. Since the screw spikes pullout resistance was already investigated in previous tests,[18] this test will enable the assessment of the fastening clips pullout resistance as well as the identification of the contributions of the screw spikes and the fastening clips to the pullout resistance of the entire system. For this test, the crosstie specimens were cut into 3 ft (0.91 m) long segments and the rail was cut into a 20 in. (50.8 cm) long segment. The complete rail and fastening system assembly was installed using the recommended setup D predrilled pilot holes as mentioned earlier.[18] Two steel channels section were used in order to fix the specimens to the testing bed when applying the vertical uplift loading. A 20 in. (50.8 cm) rail segment was cut and machined specifically for this test setup. The rail segment was drilled and taped from the top and then a threaded rod was installed to enable the application of tensile uplift forces. Two linear variable displacement transducers (LVDTs) were installed to monitor both the railhead and the steel bearing plate vertical displacements. The railhead displacement indicates the total uplift of the system while the steel bearing plate displacement provides an indication of the screw spikes pullout only without the fastening clip contribution. This scheme enables the identification of the contribution of both components to the overall system uplift resistance. Five specimens were tested at room temperature. Figures 6 and 7 illustrate the test configuration.

The vertical uplift load was applied until separation occurred between the rail and the assembly. The separation load was recorded and then two cycles of reloading/unloading were applied until the load reached one and a half times the separation loading. Additionally, the first specimen only was then loaded until failure. The failure was sudden and occurred in the fastening clips. The failed clip fragment was then propelled with a great force across the laboratory, which was a safety risk (see Figure 8). Therefore, the remaining specimens were not loaded to failure and were stopped after the second reloading as per AREMA recommendations. Figure 9 presents a sample of the results while Figure 10 summarizes the test results for all the tested specimens.

In Figure 9, the measurement designated as "Rail Head" indicates the total uplift of the system while the measurement designated as "Rail Plate" provides an indication of the screw spikes pullout only without the fastening clip contribution. Thus, the contribution of the fastening clips is the difference between the two measurements. Inspection of Figure 9 reveals that the rail fastening clips were the most significant contributor to the uplift resistance of the entire system. The contribution of the screw spikes was relatively insignificant compared to that of the fastening clips, i.e. about 7.0% on average at failure. Naturally, these contributions would change if cut spikes were used instead of the screw spikes. However, in this configuration, the fastening clips were the main contributors to the system uplift resistance as evident by the

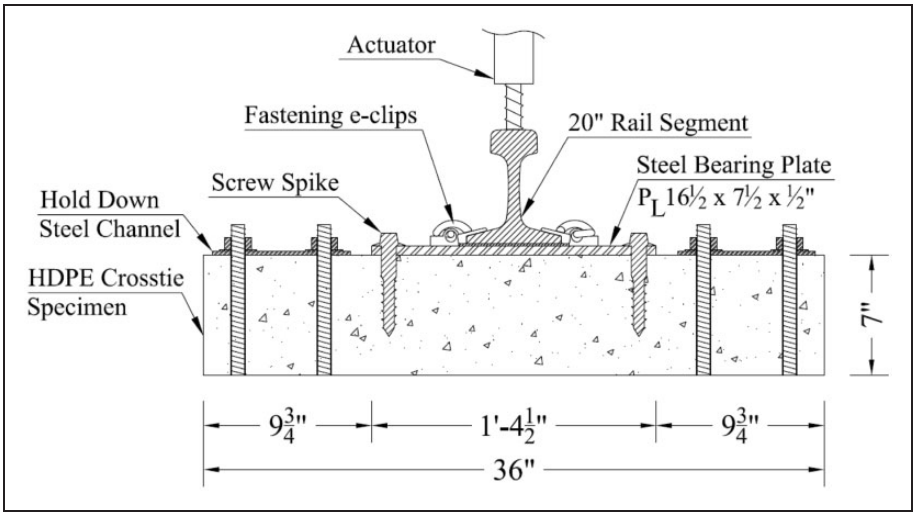

Figure 6. Fastener uplift test schematics (all units are in inches, $1'' = 2.54$ cm).

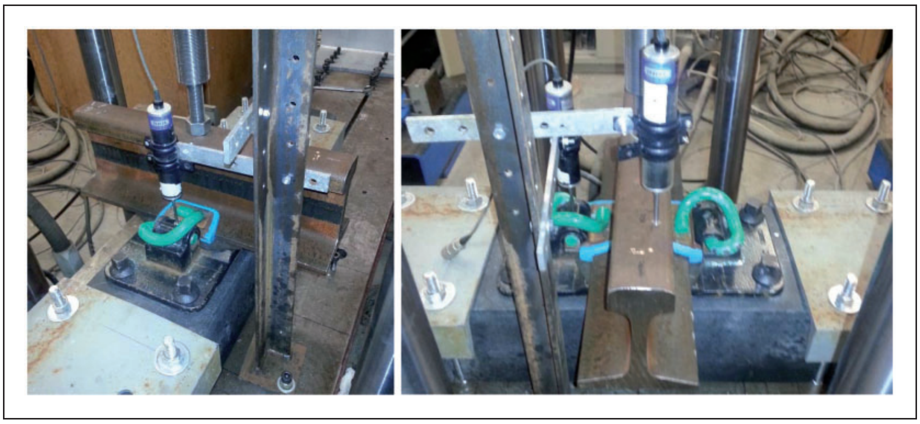

Figure 7. Fastener uplift test setup.

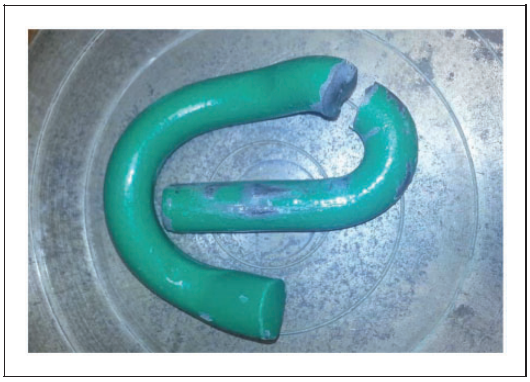

Figure 8. Failure of the fastening clip.

fracture of the clips shown in Figure 8. The response of the fastening clips was similar to the normal compliance of steel with two distinct phases: elastic and plastic. The first separation load occurred at or shortly after the yielding of the clips. After unloading, most of the deflection was recovered, with a small permanent deformation. However, after reloading to 1.5 separation load, the permanent deformation significantly increased, which indicates that the clips transitioned into the plastic region. It is curious to note that after unloading, the deflection was recovered with a steeper slope than that of the proportionality limit which was not expected. This is likely to be a result of the fastening clip's complex geometry as it is not subjected to pure tension/compression. Figure 10 presents a summary of all the tested specimens.

Inspection of Figure 10 reveals and further validates the minor contribution of the rail screw spikes. Moreover, it also validates that, at the separation load, the specimens were at or shortly after yielding, as after the first reloading the deformation at the separation load was almost identical. However, at the second reloading, the deformation was much larger; there was obvious permanent deformation in addition to the elastic deformations. Another important indication was the consistency of the results, which is indicated by the error bars. While the clips were still in the elastic range, the consistency was high,

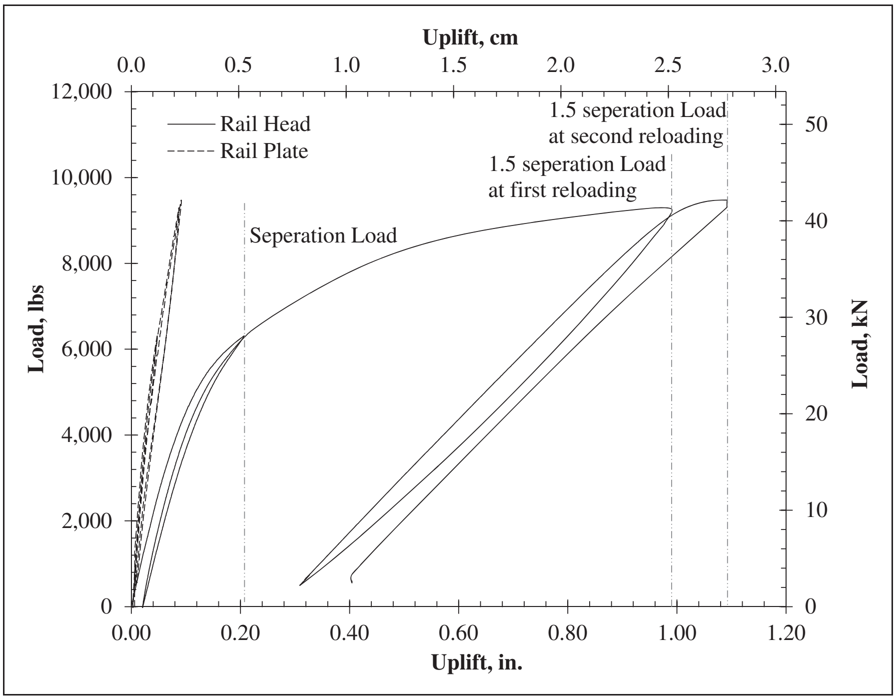

Figure 9. Fastener uplift sample test result.

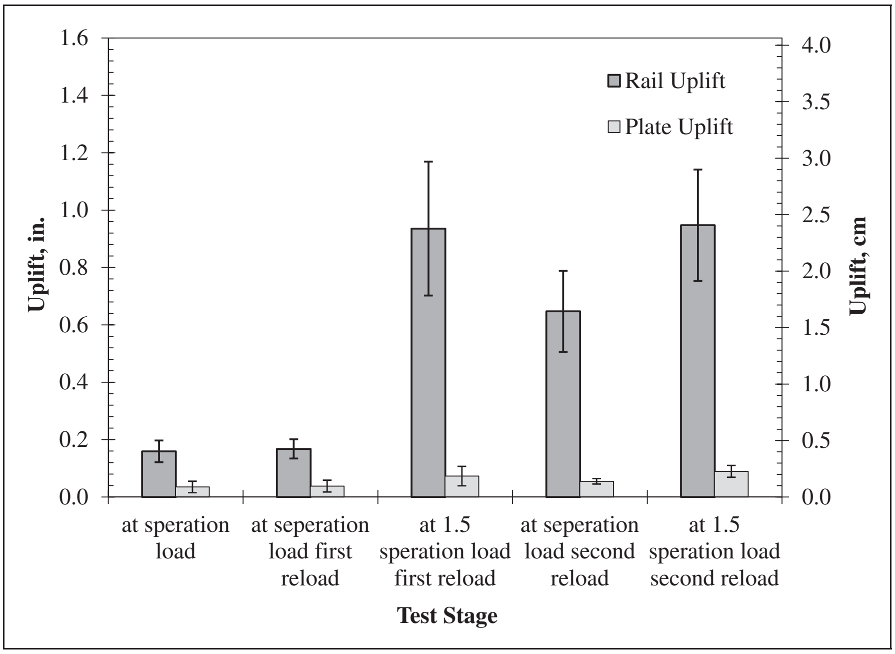

Figure 10. Fastener uplift test result summary for all the tested specimens.

represented by the small error bars. On the other hand, the larger error bars indicate that clips have transitioned into plastic range.

Fastener repeated load

The fastener repeated load test was performed by subjecting the complete system to fatigue loading cycles. It was conducted to measure the ability of the complete system to resist cycles of vertical and horizontal loading. The durability of the crossties and the fastening system assembly can be assessed by quantifying the damage occurring after three million cycles of fatigue loading. The magnitude and frequency of the fatigue loading cycles are selected to simulate the expected loading on the system during its service life, i.e. the load and frequency of train wheel passes. As such, trains would have separate loading

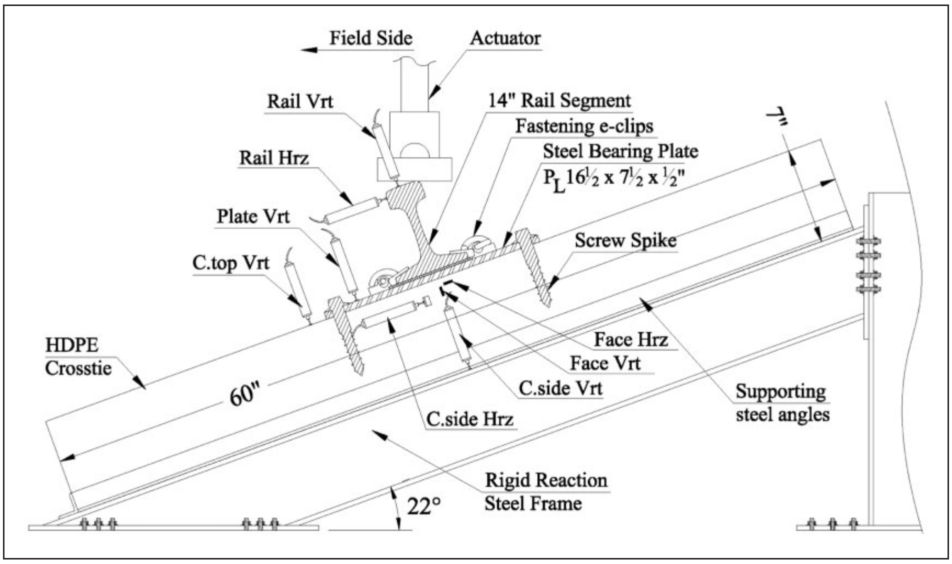

Figure 11. Test schematics and measurement designations for LVDTs and strain gauges.

configurations resulting in different expected lives. Additionally, the effect of the accelerated, continuous loading in a laboratory setting is magnified compared to real applications where the system experiences rest periods between consecutive trains. Therefore, experience plays a major role in determining the loading parameters that achieve a simulation appropriate for the desired application. In past research studies, Roybal[13] elected to simulate 9000 passes of a 110-car train for two million cycles; however, each cycle consisted of two 21,000 lb (93.4 kN) loads (two actuators) with different angles of attack that accounted for vertical and horizontal loads with a loading frequency of 220 cycles/min. The AREMA manual, AREMA Part 2—Section 2.6.3—Test 5C (15), recommends using one actuator with a 20° inclination (to account for vertical and horizontal components of the wheel load) with a load magnitude of 30,000 lb (133.45 kN) and a frequency of 300 cycles/min for a total three million cycles. This configuration does not correspond to a specific train, but rather recommended as a general qualification criterion for crosstie systems. In this study, the AREMA recommendations were adopted with two minor modifications. Figure 11 illustrates the test schematics and the different designations used for each measurement recording instruments.

For this test, the crosstie specimens were cut into 60 in. (152.4 cm) long segments and the rail was cut into a 14 in. (35.56 cm) long segment. The complete rail and fastening system assembly was installed using setup D predrilled pilot holes as mentioned earlier.[18] The specimens were then mounted on an inclined rigid reaction steel frame with supporting angles encasing them for the sides and the bottom. The steel frame was manufactured with an inclination angle of 22° to simulate, using only one actuator, the vertical and horizontal components of the rail wheel loading, which yields a lateral to vertical load ratio of 0.4 ($L/V = 0.4$). This is the first of the two minor modifications applied to the AREMA recommendations, i.e. using 22° inclination angle instead of 20° which provides $L/V = 0.4$ instead of 0.36. The authors believe that $L/V = 0.4$ is a more conservative representation of the wheel load components especially in the case of curved tracks. The lateral component of the wheel load is more critical than the vertical component, as it produces lateral deformations leading to gauge widening and derailment. The second modification was in the loading range. The AREMA manual recommends the fatigue loading range to be from 0.6P upward to 30,000 lb (133.45 kN) downward with a frequency of 300 cycles/min (where P is the separation load acquired from the fastener uplift test; thus $0.6P = 3500$ lb (15.57 kN)). However, as illustrated in Figure 11, the loading was applied as a point load, using a single actuator and the loading range was shifted to retain the fatigue stress range constant. The loading range used in this study was from 1500 lb (6.67 kN) downward to 35,000 lb (155.69 kN) downward. This modification maintained the same fatigue stress range; however, it shifted it from tension–compression to compression–compression. This alteration is less critical when studying the fastening system components contributing to its uplift resistance, i.e. rail spikes and fastening clips. However, it is significantly more critical for the HDPE crossties, rail pads, and bearing plate, which was favorable considering the scope of this research program. Due to the higher magnitude of the applied load, the loading frequency was kept at 3 Hz, i.e. 180 cycles/min, for added safety, which extended the testing time of one specimen to approximately 12 days in order to reach three million cycles.

To record the different deformations and strains, six LVDTs and four strain gauges were installed, as illustrated in Figure 11 and depicted in Figures 12 and 13. The LVDTs were used to monitor the deformations in the specimens: railhead vertical (designated as "Rail vrt") and horizontal deformations (designated as "Rail Hrz"), steel bearing plate vertical deformation (designated as "Plate Vrt"), crosstie's top surface vertical deformation (designated as "C.top Vrt"), and crosstie's side vertical and horizontal deformations (designated as "C.side Vrt" and "C.side Hrz," respectively). The LVDTs were equipped with specially made, color-coded bolts at their tips to enable their retraction without affecting

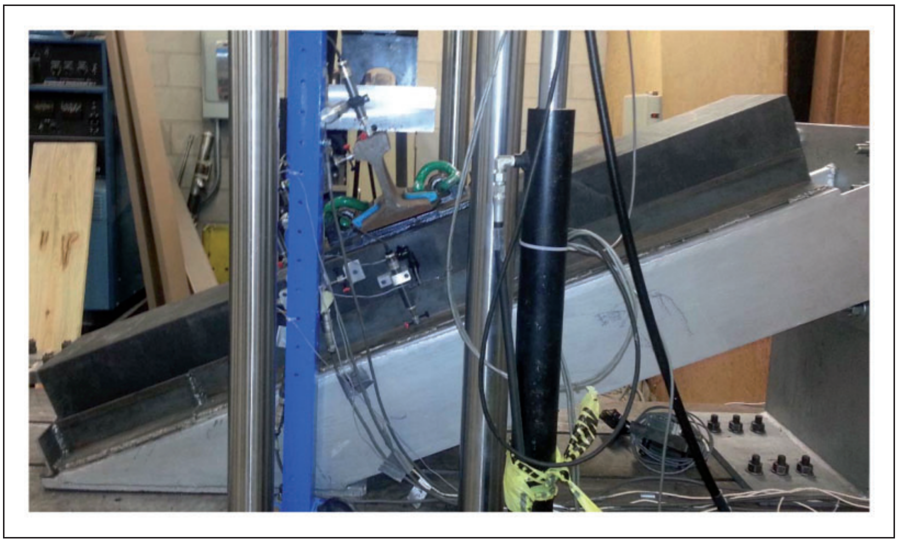

Figure 12. Test setup.

Figure 13. Test instrumentation and strain gauge installation.

accuracy, while the loading cycles were applied to avoid damage. The LVDTs were released only when recording the deformations: before fatigue loading (initial), then after 10,000 cycles, 50,000 cycles, 100,000 cycles, 250,000 cycles, and then every 250,000-cycle intervals until 3,000,000 cycles were reached. The strain gauges were mounted on the crosstie to measure the strains in the specimen throughout the whole duration of the test. The four strain gauges were installed as two T-rosettes (vertical and horizontal strains) on both sides of the crossties (designated as "Face Vrt," "Face Hrz," Back Vrt," and "Back Hrz").

Five specimens were tested and the data were recorded. The test was stopped after three million cycles and flexural tests were conducted on the specimens after fatigue to quantify the damage in the HDPE crosstie compared to new ones. No failure occurred in any of the fastening system components or the HDPE crossties throughout all the tests. Figure 14 presents the HDPE crosstie, rail pad, and the screw spike after the three million cycles showing the extent of the damage occurring in each component.

As depicted in Figure 14, the HDPE crosstie showed minor, superficial surface abrasion under the steel bearing plate. The abrasion occurred toward the field side while the gauge side showed little damage. Similarly, the rail pads showed almost no damage toward the gauge side while the filed side showed deterioration and minor disintegration of the rubber material, as shown in Figure 14. Minor bite marks occurred on the filed side screw spikes as well. The fastening clips and the steel bearing plate showed no signs of deterioration or damage. The deformation reading was collected and the peak deformation was identified for each recorded cycle. Figure 15 presents the peak deformations of the system at all the recorded cycles for a sample specimen on a log–log scale and Figure 16 presents the peak strains recordings for the same specimen.

Inspection of Figure 15 reveals that the deformations experienced in the system were small, ranging from 0.05 to 0.35 in. (0.13 to 0.89 cm) with the maximum occurring at the railhead horizontal movement as expected. The minimum deformations occurred in the HDPE crosstie. The strain gauges reading further confirmed the LVDT results; the strains experienced by the HDPE crosstie were low, with the maximum strain reaching 798×10^{-6} (in./in.; cm/cm) (refer to Figure 16). Moreover, the peak deformations of the system did not change significantly throughout the test duration. As noticed from Figure 15, most of the recordings were almost constant (parallel to the x-axis) throughout the test which indicates that the peak deformations at the beginning and end of the fatigue cycles did not increase by much, thus no significant damage occurred. To better illustrate and quantify this damage, the gain in peak deformations was calculated by subtracting the initial deformation, i.e. initial peak deformation was shifted to zero, and the resulting gain in peak deformations (indication of the permanent deformation) was plotted in Figure 17.

Inspection of Figure 17 reveals that the railhead horizontal movement is the most affected part of the system by the accumulated fatigue deterioration. The railhead horizontal movement directly affects the gauge length thus has to be monitored closely. Apart for the horizontal railhead movement, all the accumulated permanent deformations due to fatigue were minor. Figure 18 summarizes the results of all the five tested specimens using the maximum gained peak deformation after three million cycles, which provides an indication of the permanent deformations in the system. The AREMA manual recommends a maximum permanent deformation of 0.2 in. (0.51 cm) for the railhead lateral deflection.

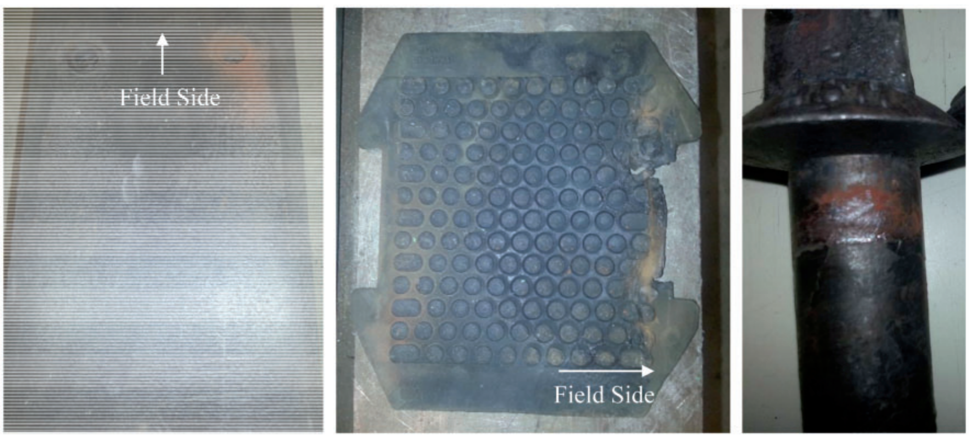

Figure 14. HDPE crosstie abrasion, pad damage, and screw spikes bite marks after three million cycles.
HDPE: high-density polyethylene.

As shown in Figure 18, the maximum gained peak vertical deformation of the railhead (average of 0.019 in. (0.048 cm)) is an indication of the rail seating, which occurred due to installation tolerances and imperfections. The railhead lateral movement is of great interest as it indicates the gauge widening. The difference between the bearing plate and the crosstie's surface vertical deflections quantifies the bearing plate indentation in the HDPE material, which averaged 0.039 in. (0.099 cm). It is important to note that the crosstie's top surface vertical deflection was almost zero which means that, outside the vicinity of the bearing plate (refer to Figure 11 for the LVDTs' locations), the crosstie experienced no damage or permanent deformation as a result of fatigue loading. Another important observation to note is that bearing plate vertical deflection gained was greater than that of the railhead vertical deflection, which, at first could appear illogical. However, after considering the location of both LVDTs, it becomes apparent that the bearing plate vertical deflection would experience more damage because it is located on the field side as opposed to the railhead vertical deflection, which is in the center of the system (refer to Figure 11). The applied vertical and horizontal loads create bending actions that affected the field side more significantly than the other areas, which was evident by the visual investigation of the component's damage shown

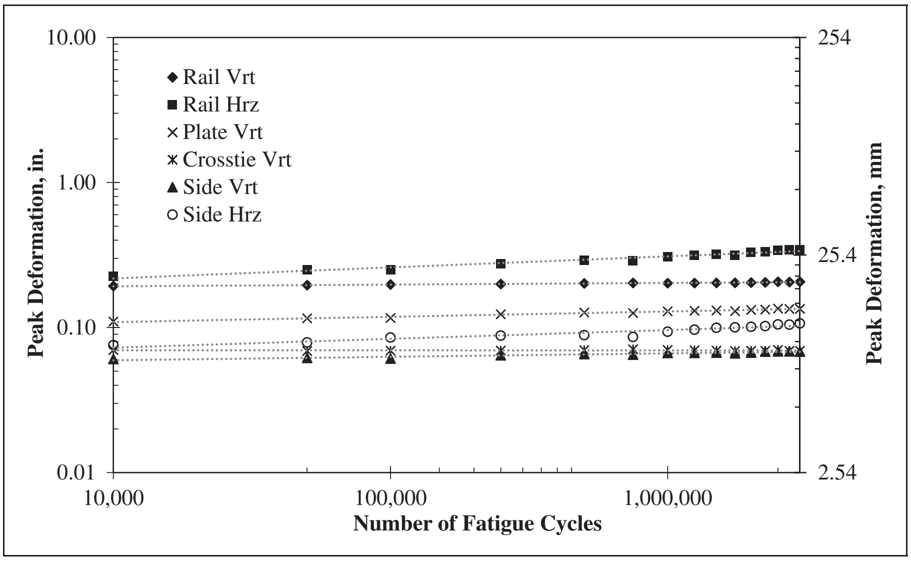

Figure 15. Peak deformations versus number of cycles for a sample specimen.

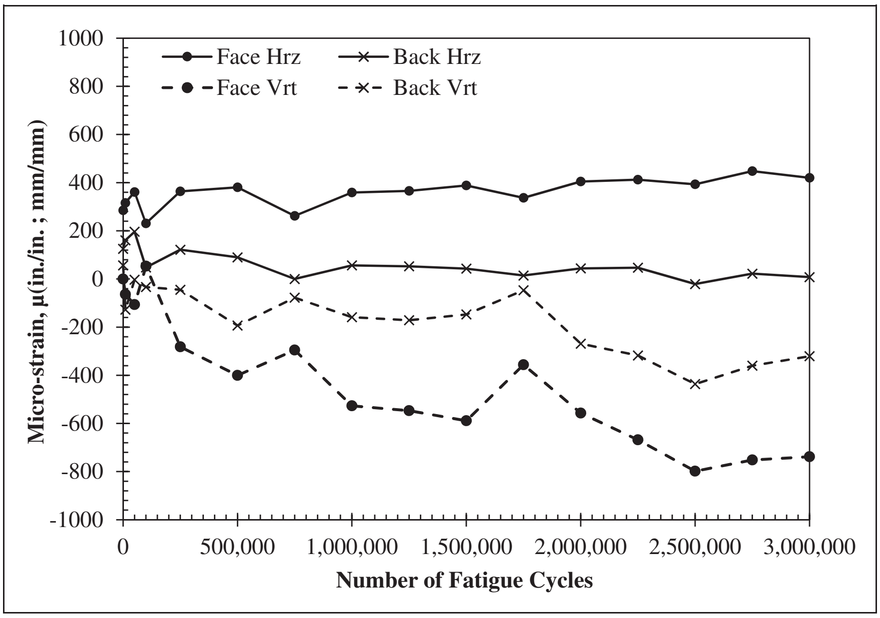

Figure 16. Peak stains readings versus number of cycles for a sample specimen.

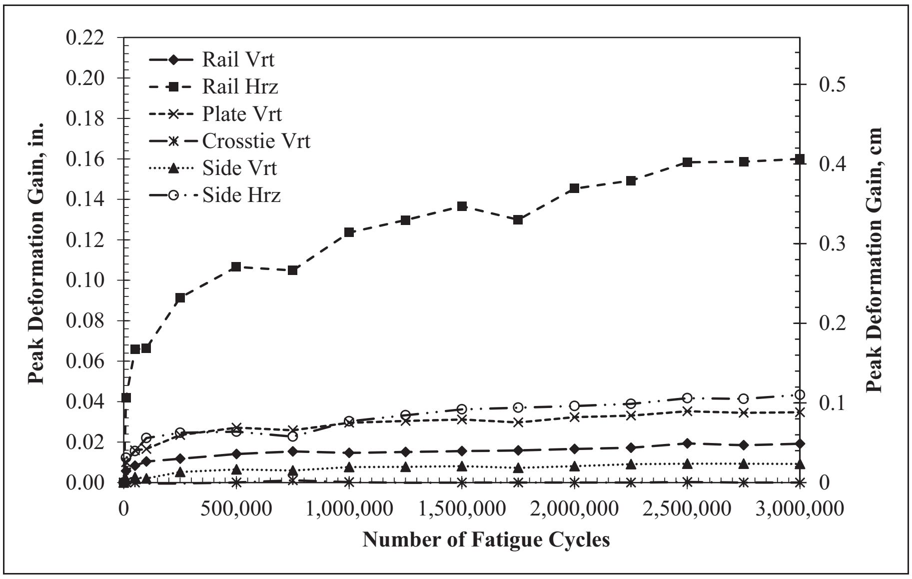

Figure 17. Peak deformation gain versus number of cycles.

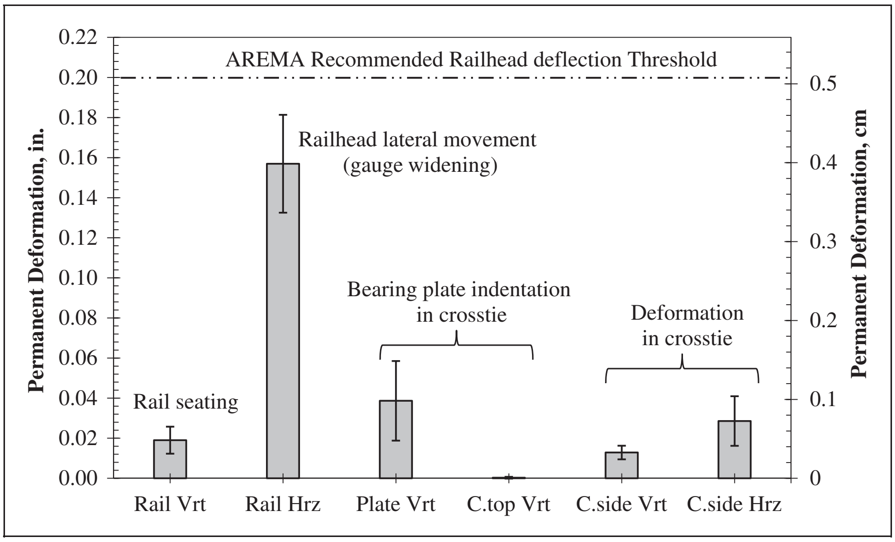

Figure 18. Maximum gained peak deformation after three million cycles for all the tested specimens.

in Figure 14. Finally, the crosstie side defamations indicate deterioration in the HDPE material. As observed before, apart for the horizontal railhead movement, all the accumulated permanent deformations due to fatigue were minor.

After the fatigue tests were concluded, the damaged specimens were then tested using a three-point bending configuration as per the AREMA recommendations: AREMA Part 2—Section 2.2.3—Test 1C.[15] The results of the flexural test were compared with the new crossties, previously tested by the authors as part of this research effort.[16] All the tested specimens failed at the mid-span of the crosstie and not at the predrilled holes' locations nor at the filed side, as shown in Figure 19. The behavior of the crosstie was similar to the new crossties tested before. Figure 20 presents the stress–strain relationship for the new and fatigued crossties. Table 1 summarizes and compares the flexural parameters of the new and fatigued crossties.

At first glance of Figure 20, the difference between the new specimens and the specimens after fatigue is not very clear. However, after careful investigation, it becomes clear that there is a noticeable difference in the initial modulus between the two, i.e. the initial slope of the stress–strain curve was reduced after fatigue. This observation was confirmed by Table 1; the initial tangent modulus dropped 16% due to the fatigue damage. From the data presented in Figure 20 and Table 1, the following can be concluded. In the initial stage of the test, the specimens' resistance is mainly dependent on the HDPE material, as the fiber reinforcements were not yet activated. The HDPE material experienced deterioration due to the

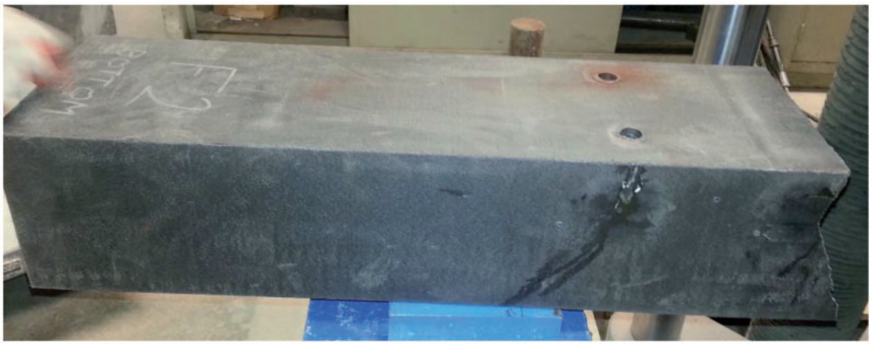

Figure 19. Failure of the specimens in flexure after three million fatigue cycles.

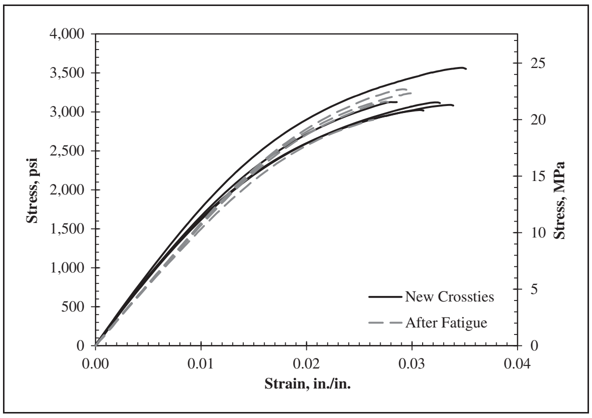

Figure 20. Stress–strain relationship for the new and fatigued crossties.

Table 1. Summary of the flexural parameters for both the new and fatigued crossties.

Crosstie condition	New[a] psi	New[a] MPa	After fatigue psi	After fatigue MPa	After fatigue/ New (%)
Modulus of rupture	3185	21.96	3131	21.59	98
Ultimate strain, $\mu\varepsilon$	32,257		28,630		89
Initial tangent	190,151	1311.05	159,975	1102.99	84
Modulus at 600 psi (4.14 MPa)	183,228	1263.31	158,275	1091.27	86
Modulus at 1% strain	166,205	1145.93	154,110	1062.55	93

[a]Flexural test data for the new crossties were tested previously by the authors.[15]

fatigue test, which reduced the initial modulus as evident by the 16% reduction. As the test progresses, the fiber reinforcements get gradually activated reducing the effect of the HDPE material deterioration, as evident by the diminishing reduction in the flexural moduli as the test progresses, e.g. 14% reduction at 600 psi (4.14 MPa) and then a 7% reduction at 1% strain. The modulus of rupture remained almost constant, dropping only 2%, as it is mainly dependent on the ultimate strength of the fiber reinforcement, which was unaffected by the fatigue cycles. The ultimate strain however is dependent on the ductility of the HDPE material, thus experienced a reduction of 11%.

Summary and conclusion

In this study, an experimental investigation was carried out to understand and assess the performance of the full rail support system, i.e. the rail section, fastening system, and recycled HDPE crossties. The static test methods, recommended by the AREMA manual, were used to evaluate the performance of the rail support system when subjected to uplift forces and longitudinal loading in the direction of the rail track. In addition, the long-term behavior of the rail support system while being subjected to repeated loading for three million fatigue cycles was evaluated using cyclic testing. All the specimens survived the fatigue loading with minimal degradation, which highlights the potential of HDPE materials if properly optimized and engineered. Highlighted below are the findings and conclusions of this paper:

1. The longitudinal resistance of the full system is provided mainly by friction between the rail and the lower bearing plate and the upper insulators. The specimens' longitudinal resistance surpassed the AREMA recommendations by a significant margin. Moreover, the maximum static friction should not be reached under normal operating conditions, if properly designed.
2. The rail fastening e-clips were the most significant contributor to the uplift resistance of this system. The contribution of the screw spikes was relatively insignificant: contributing only 7% at failure.
3. The response of the fastening clips was similar to steel compliance with elastic and plastic phases. After unloading, the deflection was recovered

with a steeper slope than that of the proportionality limit which is likely to be a result of the fastening clip's complex geometry.
4. Throughout all the fatigue tests, no failure occurred in any of the fastening system components or the HDPE crossties.
5. After three million cycles of fatigue loading, the HDPE crosstie experienced superficial surface abrasion under the steel bearing plate toward the field side. Similarly, the rail pads showed almost no damage toward the gauge side while the filed side showed deterioration and minor disintegration of the rubber material. Minor bite marks occurred on the filed side screw spikes. The fastening clips and the steel bearing plate showed no signs of deterioration or damage. However, the HDPE crosstie experienced material yielding, which was not initially detected by visual inspection.
6. The deformations and strains experienced in the system during the fatigue testing were very low with the maximum occurring at the railhead horizontal movement and the minimum in the HDPE crosstie.
7. The railhead experienced the most significant permanent horizontal deformation. Minor indentation and material yielding were experienced by the HDPE crossties.
8. The system survived the fatigue test with normal wear and without any critical or major issues.
9. After being subjected to three million cycles of fatigue loading, the HDPE crossties experienced a reduction in the stiffness and strength. Even though this reduction was small, it was significant enough to be taken into consideration when predicting service lives.
10. The results of this experimental study illustrate that HDPE crossties have great performance and durability to be considered as a viable solution in real application after further field testing.

Acknowledgements

Our thanks are also extended to the CTA and Tangent Technologies, LLC for their support. The authors would like to acknowledge the help of Maen Farhat, Mostafa Al-Obaidi, Mustapha Ibrahim, and Momenur Rahman in the preparation and testing of the specimens.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was funded by the New University Rail Center (NURail) and the U.S. Department of Transportation—RITA.

References

1. Thierfelder T and Sandstrom E. The creosote content of used railway crossties as compared with European stipulations for hazardous waste. *Sci Total Environ* 2008; 402: 106–112.
2. Zagier AS. Creosote: 'Witch's Brew'. http://www.mindfully.org/Pesticide/2004/Creosote-Illness-Death24may04.htm (accessed 24 May 2014).
3. Morris T. Poisonous railway sleepers pose health risk. http://lists.greens.org.au/mailman/public/media/2008-October/010679.html (October 2008, accessed 28 May 2014).
4. Pruszinski A. *Review of the landfill disposal risks and the potential for recovery and recycling of preservative treated timber*. Environmental Protection Agency Report. South Australia: Sinclair Knight Merz, 1999.
5. Coffin B. Coalition sues EPA to ban toxic wood preservatives. *Risk Mngmnt* 2003; 50: 2.
6. Schunt JH. They've been working on the railroad. April 2004. *Plastic Technology* (Online magazine), www.ptonline.com (accessed 26 May 2014).
7. Goldgaber A. Plastic railroad ties: growing market for alternative materials, www.SmallcapInsights.com (2009, accessed 5 May 2014).
8. Weart W. With a weak economy at the forefront and railroad spending cuts on the horizon, crosstie demand will be restrained for the rest of '09, then drop in '10. *Progressive Railroading* (Online magazine), http://www.progressiverailroading.com/ (accessed 10 June 2014).
9. Jackson LM and Nosker TJ. Technology, applicability, and the future of thermoplastic lumber. In: *The DoD corrosion conference*, Gaylord National, Washington, DC, USA, 10–14 August 2009.
10. Manalo A, Aravinthan T, Karunasena W, et al. A review of alternative materials for replacing existing timber sleepers. *Compos Struct* 2010; 92: 603–611.
11. Jimenez R. *Vertical track modulus in plastic composite ties test zones at FAST*. Report no. DOT/FRA/ORD-03/13, 2003. Pueblo, CO: Transportation Technology Center, Inc.
12. Lampo RG, Nosker TJ and Sullivan HW. Development, testing, and applications of recycled plastic composite cross ties. In: *World Congress on Railway Research*, Edinburgh, Scotland, UK, 28 September–1 October 2003.
13. Roybal S. *Composite crosstie test cyclic load*. Report no. P-09-003, 2009. Pueblo, CO: Transportation Technology Center, Inc.
14. Reiff R and Trevizo C. *Cracking and impact performance characteristics of plastic composite ties*. Report no. DOT/FRA/ORD-12/03, 2012. Pueblo, CO: Transportation Technology Center, Inc.
15. American Railway and Maintenance-of-Way Association. Evaluative tests for tie systems.

In: *AREMA Manual for Railway Engineering*, 2011, Volume 1, Chapter 30, pp.30-2-1–30-2-20. Lanham, MD.
16. Lotfy I, Farhat M, Issa M, et al. Flexural behavior of high-density polyethylene railroad crossties. *J Rail Rapid Transit* 2016; 230(3): 813–824.
17. Lotfy I, Farhat M and Issa M. Temperature effect on the performance of glass fiber reinforced high density polyethylene composite railroad crossties. *J Rail Rapid Transit* 2016; 230(4): 1145–1157.
18. Lotfy I, Farhat M and Issa M. Effect of pre-drilling, loading rate and temperature variation on the behavior of railroad spikes used for high density polyethylene crossties. *J Rail Rapid Transit* 2017; 231(1): 44–56.